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TECHNICAL NOTE
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APPLICATION OF RATE-TEMPERATURE PARAMETERS TO TENSILE DATA FOR MAGNESIUM ALLOYS AND A RELATION BETWEEN THE LARSON-MILLER CONSTANT AND THE ACTIVATION ENERGY

By Charles R. Manning, Jr.

Langley Research Center
Langley Field, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON May 1960

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APPLICATION OF RATE-TEMPERATURE PARAMETERS TO TENSILE DATA FOR MAGNESIUM ALLOYS AND A RELATION BETWEEN THE LARSON-MILLER CONSTANT AND THE ACTIVATION ENERGY

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SUMMARY

The Larson-Miller and Dorn rate-temperature parameters were successfully applied to published data to take into account the effect of strain rate and temperature on the tensile properties of six magnesium alloys at strain rates from 0.005 minute^{-1} to 5.0 minute^{-1} and temperatures to 800° F. Master curves are presented which summarize extensive tensile data on the magnesium alloys and may be used to predict tensile strength and tensile yield strength for any combination of strain rates and temperatures up to 5.0 minute^{-1} and 800° F, respectively. The values of the Larson-Miller constant C and the activation energy ΔH were determined for each material.

A relation was found between C and ΔH for magnesium and aluminum alloys. This relation was found to be insensitive to stress and strain rate.

INTRODUCTION

In recent years many successful attempts have been made to correlate the effects of time and temperature in creep and stress-rupture applications by the use of parameters. Fewer efforts have been made to use parameters to predict the effects of strain rate and temperature on the tensile strength and tensile yield strength of materials. Two of the earliest attempts to correlate tensile data were made by Zener and Hollomon (ref. 1) and MacGregor and Fisher (ref. 2).

In this paper the Dorn parameter (ref. 3) and the Larson-Miller parameter (ref. 4) are applied to tensile data, taken from reference 5, for six magnesium alloys. The Larson-Miller constant C and the constant associated with the Dorn parameter (the activation energy ΔH)

were determined for each material. Master curves for tensile strength and tensile yield strength were constructed for each material.

A relation is presented between the values of C and ΔH which were determined in the application of the parameters to the tensile strength and tensile yield strength of the magnesium alloys. This relation was also applied to creep and stress-rupture data for pure aluminum and various aluminum alloys.

SYMBOLS

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P_D	Dorn parameter
P_L	Larson-Miller parameter
C	Larson-Miller constant
ΔH	activation energy, cal/mole
$\dot{\epsilon}$	strain rate, min^{-1}
R	gas constant, taken as 1.11 cal/mole/$^{\circ}F$
T	absolute temperature, $^{\circ}R$
σ	stress, ksi
A	constant in Arrhenius equation: $\dot{\epsilon} = Ae^{-\frac{\Delta H}{RT}}$

EFFECT OF STRAIN RATE AND TEMPERATURE ON TENSILE PROPERTIES

The materials included in the investigation to determine the effect of strain rate and temperature are HK31A-H24, AZ31B-H24, and HM21A-T8 magnesium-alloy sheet and HM31XA-F, ZK60A-T5, and ZK60A-F magnesium-alloy extrusion. (See ref. 5.) The test specimens were flat with a standard reduced test section and were heated in approximately 10 seconds by passing an electric current through them. They were held at temperature approximately 5 seconds before testing. Each test was run at a constant strain rate and constant temperature. The strain rates ranged from 0.005 $minute^{-1}$ to 5.0 $minute^{-1}$ and the test temperatures ranged from 75° F to 900° F.

The effects of strain rate on the tensile properties of six magnesium alloys may be seen in figures 1 to 6, and the effects of temperature in figures 7 and 8. The isothermal curves of figures 1 to 6 show, for each material, the experimental results and the results of calculations based on two different parameters, as described in a subsequent section. Figures 7 and 8 summarize the tensile-strength and tensile-yield-strength data, respectively, for a strain rate of 0.005 minute^{-1}. Two of the materials were not included in figure 7 because the data were not available. An examination of figures 7 and 8 indicates that the thorium alloys (HM31XA-F, HM21A-T8, and HK31A-H24) have higher tensile properties above 200° F than the alloys without thorium (ZK60A-T5, ZK60A-F, and AZ31B-H24). The thorium alloys appear to be much less strain-rate sensitive than the other alloys.

RELATION BETWEEN LARSON-MILLER AND DORN PARAMETERS

Arrhenius (ref. 6) showed that a relationship exists between the rate at which a certain process takes place under certain conditions, the activation energy, and the temperature. This relation is often written as

$$\dot{\epsilon} = Ae^{-\frac{\Delta H}{RT}} \tag{1}$$

where $\dot{\epsilon}$ is the rate, ΔH is the activation energy, R is the gas constant, A is a constant, and T is the absolute temperature. This relation may also be expressed as

$$T\left(C - \log_{10} \dot{\epsilon}\right) = \frac{\Delta H}{2.3R} \tag{2}$$

or

$$\frac{\Delta H}{2.3RT} + \log_{10} \dot{\epsilon} = C \tag{3}$$

where $C = \log_{10} A$.

The left-hand side of equation (2) is the Larson-Miller parameter (ref. 4), which has been applied to creep with $\dot{\epsilon}$ taken as the minimum creep rate; C is a constant assumed to be independent of stress, and T is the absolute temperature in °R. The parameter is a function of stress and equation (2) implies that ΔH varies with stress.

The left-hand side of equation (3) is the Dorn parameter (ref. 3), which also has been applied to creep with $\dot{\epsilon}$ taken as the minimum creep rate; ΔH is taken to be a constant and T is the absolute temperature in °R. This parameter is also a function of stress and equation (3) implies that C varies with stress.

The essential difference between the two parameters, shown in the previous paragraphs, may also be illustrated in a plot of $\log_{10} \dot{\epsilon}$ against $1/T$ for various constant stresses. If ΔH is considered a variable and C a constant in equation (2), the isostress curves will converge at a point $(-C,0)$. If C is considered a variable and ΔH a constant in equation (3), the isostress curves will be parallel with a slope ΔH. The two parameters thus involve basically different concepts.

The point of view that ΔH may be taken as a constant at temperatures above about 45 percent of the melting temperature has considerable experimental backing (ref. 7). There is also considerable experimental evidence that C may be taken as a constant in this region.

APPLICATION OF PARAMETERS TO EXPERIMENTAL DATA

Method of Determining Constants

The Larson-Miller parameter P_L is herein applied to tensile data for magnesium alloys. The parameter used for tensile applications is similar to the parameter used for creep and is

$$P_L = T\left(C - \log_{10} \dot{\epsilon}\right) \tag{4}$$

where $\dot{\epsilon}$ is the strain rate. The value of C which gave the best correlation of the data was determined for each material in the following manner. A value of 20 was initially assumed for C, and a master curve was constructed. The value of C for each material was then varied until a continuous master curve was obtained. The value of C for each material can also be determined from isothermal data (figs. 1 to 6) by means of the following expression which is derived from equation (4):

$$C = \frac{T_1 \log_{10} \dot{\epsilon}_1 - T_2 \log_{10} \dot{\epsilon}_2}{T_1 - T_2} \tag{5}$$

where, at a given stress, $\dot{\epsilon}_1$ is the strain rate at a temperature T_1 and $\dot{\epsilon}_2$ is the strain rate at a temperature T_2.

The Dorn parameter P_D was also applied to the tensile data for the six magnesium alloys and is

$$P_D = \frac{\Delta H}{2.3RT} + \log_{10} \dot{\epsilon} \tag{6}$$

where $\dot{\epsilon}$ is the strain rate. The value of ΔH for each material was determined from isothermal data (figs. 1 to 6) by means of the following expression, which can be derived from either Zener and Hollomon's function $\dot{\epsilon} e^{\frac{\Delta H}{RT}}$ (ref. 1) or from equation (1):

$$\Delta H = \frac{R\left(\log_e \dot{\epsilon}_2 - \log_e \dot{\epsilon}_1\right)}{\frac{1}{T_1} - \frac{1}{T_2}} \tag{7}$$

At a given stress, $\dot{\epsilon}_1$ is the strain rate at temperature T_1 and $\dot{\epsilon}_2$ is the strain rate at temperature T_2. The individual values of ΔH at temperatures above 45 percent of the melting temperature (above about 400° F) were approximately constant except for HK31XA-F magnesium alloy. The value of ΔH used for each material was the average of the values determined from the tensile strength and tensile yield strength above 400° F. In the case of HM31XA-F magnesium alloy, ΔH was determined from the data between 600° F and 700° F.

An objective method for the determination of the optimum parametric constants, based upon a least-squares method of analysis, is described in reference 8. The method can be applied to the Larson-Miller, Dorn, and Manson-Haferd parameters and will give results which do not depend upon individual judgment.

Master Curves

Master curves for the tensile strength and tensile yield strength, calculated by means of the Larson-Miller parameter, are shown in figures 9, 10, and 11 for the magnesium alloys. The corresponding master curves calculated by means of the Dorn parameter are presented in figures 11, 12, and 13. Values of the Larson-Miller constant C and the activation energy ΔH for the magnesium alloys are shown in table I.

The lack of scatter of the points in figures 9 to 13 indicates that either the Larson-Miller or the Dorn parameter can be used to determine the tensile strength and tensile yield strength of the six magnesium alloys. The temperatures varied from room temperature to 800° F. An examination of the master curves for each material shows that the data can be correlated equally well with either parameter down to 75° F.

The results calculated from the master curves (figs. 9 to 13) are shown as dashed curves in figures 1 to 6. A comparison of the dashed curves (obtained from the Dorn and Larson-Miller parameters) with the experimental curves in figures 1 to 6 shows that, in general, both the calculated curves are in close agreement with experimental results, except at the highest strain rate. (See fig. 1, for example.)

RELATION BETWEEN C AND ΔH

The values of the Larson-Miller constant C and the activation energy ΔH (in the Dorn parameter) for the magnesium alloys varied over a wide range, as can be seen in table I. In figure 14 an empirical linear relation is shown between C and ΔH for seven magnesium alloys. This relation is insensitive to stress, strain rate, and temperature and may be given as

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$$C = 0.0004\ \Delta H + 2.00 \tag{8}$$

where 0.0004 is the slope of the curve and 2.00 the intercept. The activation energies for the magnesium alloys in figure 14 were calculated from tensile data, but further investigation showed that the activation energies for creep for two of the magnesium alloys are of nearly the same magnitude as the activation energies obtained from the tensile data. This comparison may be seen in table I.

In order to determine whether the relationship was fairly general, values of the Larson-Miller constants and activation energies were determined for pure aluminum and three aluminum alloys from published creep data. The values of C were already determined for these materials (ref. 9) and values of ΔH were calculated by the method previously described from minimum creep-rate data given in references 3 and 10. Values of C and ΔH derived from creep data for the aluminum materials (table II) fall along the same curve (fig. 14) that was determined from the tensile data for the magnesium alloys. Sherby and Dorn (ref. 3) have shown that the activation energy of creep and flow was nearly the same for three aluminum alloys. The relationship in figure 14 seems to be fairly general as it can be applied to creep and tensile data and used for magnesium and aluminum alloys. The value of C can be determined directly from equation (8) once the value of ΔH is known.

The relation between C and ΔH may not be completely general and should be investigated further before application to other materials, such as high-temperature alloys.

An analytical relation between C and ΔH, which was previously determined (eq. (3)), is

$$C = \frac{\Delta H}{2.3RT} + \log_{10} \dot{\epsilon}$$

Equation (3) has the same form as the empirical relation (eq. (8)). If an average temperature of 1,000° R (540° F) and an average strain rate of 2.5 minute^{-1} are assumed for the magnesium alloys, equation (3) becomes

$$C = 0.00039\,\Delta H + 0.4 \tag{9}$$

Equation (9) is in close agreement with the experimental relation (eq. (8)).

CONCLUDING REMARKS

The Larson-Miller and Dorn parameters were successfully applied to tensile stress-strain data for six magnesium alloys. The master curves summarized extensive data and the results calculated from the master curves for tensile strength and tensile yield strength were in close agreement with experimental data. In general, however, caution should be exercised in extrapolating the results obtained by these parametric methods beyond the range of the data.

An empirical relation was determined between the Larson-Miller constant and the activation energy (used in the Dorn parameter) for the magnesium alloys, and this was found to hold for both stress-strain and creep applications. The relation also held for creep applications for aluminum and a number of aluminum alloys. Although the relation was successfully applied to both magnesium and aluminum alloys, it should be investigated further before application to materials other than aluminum and magnesium alloys.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., August 27, 1959.

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TABLE I

COMPUTED VALUES OF ΔH AND C FOR MAGNESIUM ALLOYS

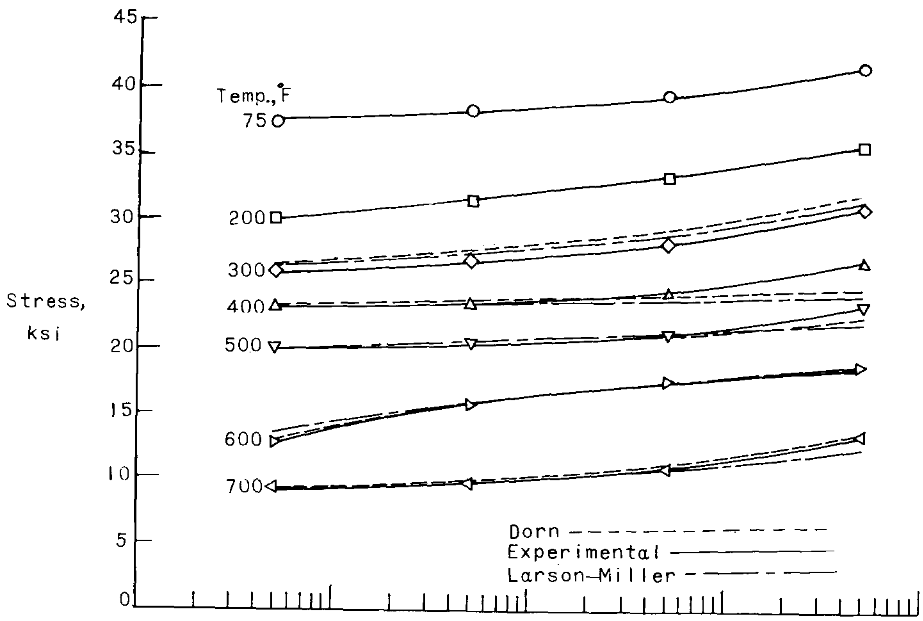
Material	ΔH from tensile test, cal/mole	ΔH from creep data, cal/mole	C for tensile data
ZK60A-T5	33,400		15.0
ZK60A-F	26,900		13.0
AZ80A-T5	29,850		14.0
HM31XA-F	90,500		47.0
HM21A-T8	57,800	62,600 (from data furnished by the Dow Chemical Co.)	25.0
HK31A-H24	44,500	45,400 (ref. 11)	20.0
AZ31B-H24	24,500		12.0

TABLE II

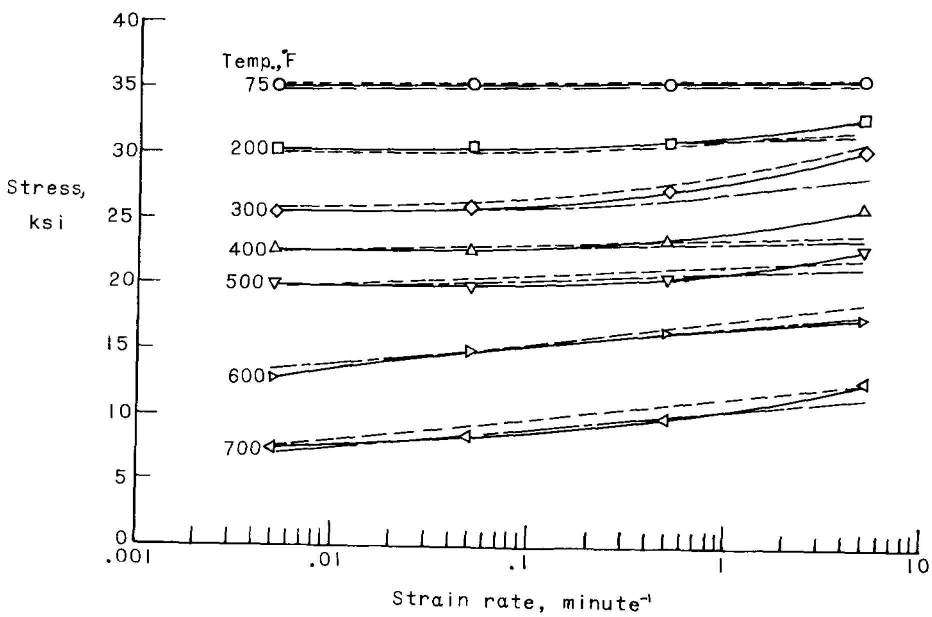
COMPUTED VALUES OF ΔH AND C FOR ALUMINUM

AND ALUMINUM ALLOYS FROM CREEP DATA

Material	ΔH, cal/mole	C
Pure aluminum	34,500 (ref. 3)	16.0 (ref. 3)
3S-H18	76,500 (ref. 10)	30.0 (ref. 9)
2024-T3	37,100 (Unpublished NASA data)	17.0 (Unpublished NASA data)
52S-H38	38,000 (ref. 10)	19.0 (ref. 9)



(a) Tensile strength.



(b) Tensile yield strength.

Figure 1.- Effect of strain rate on the tensile strength and the tensile yield strength of HM31XA-F magnesium-alloy extrusion at elevated temperatures after 5 seconds' holding time at temperature.

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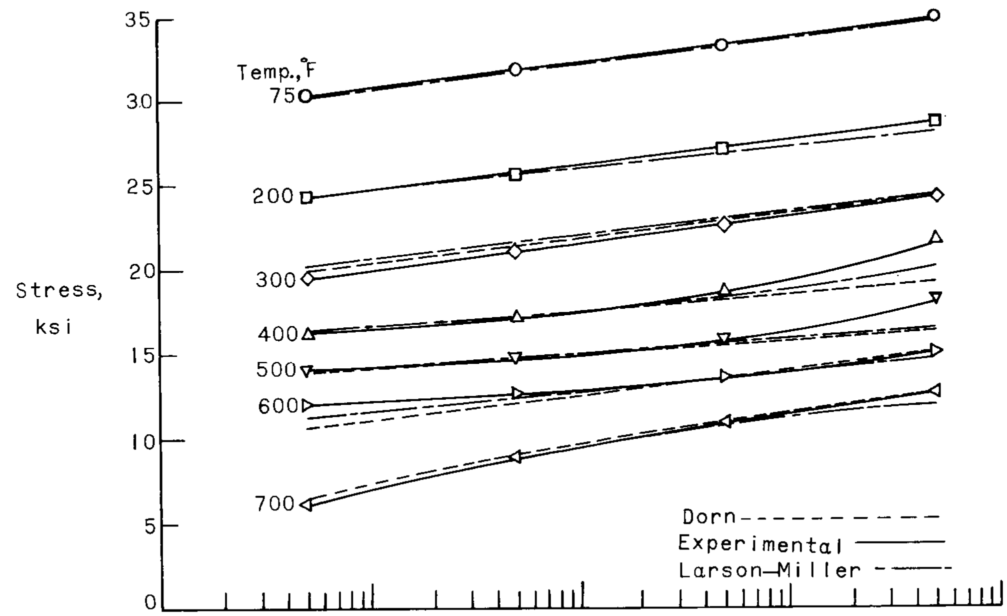
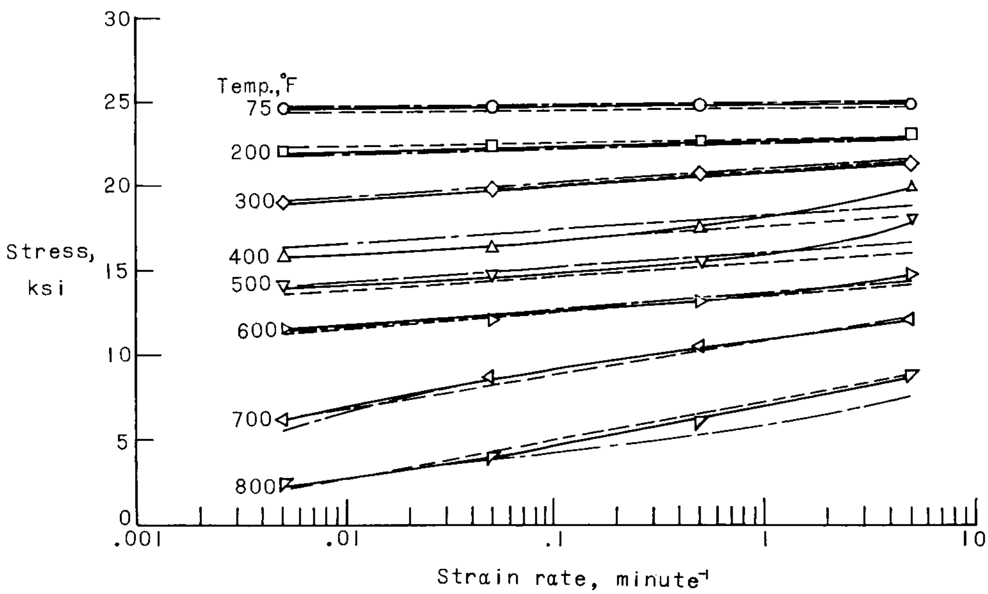
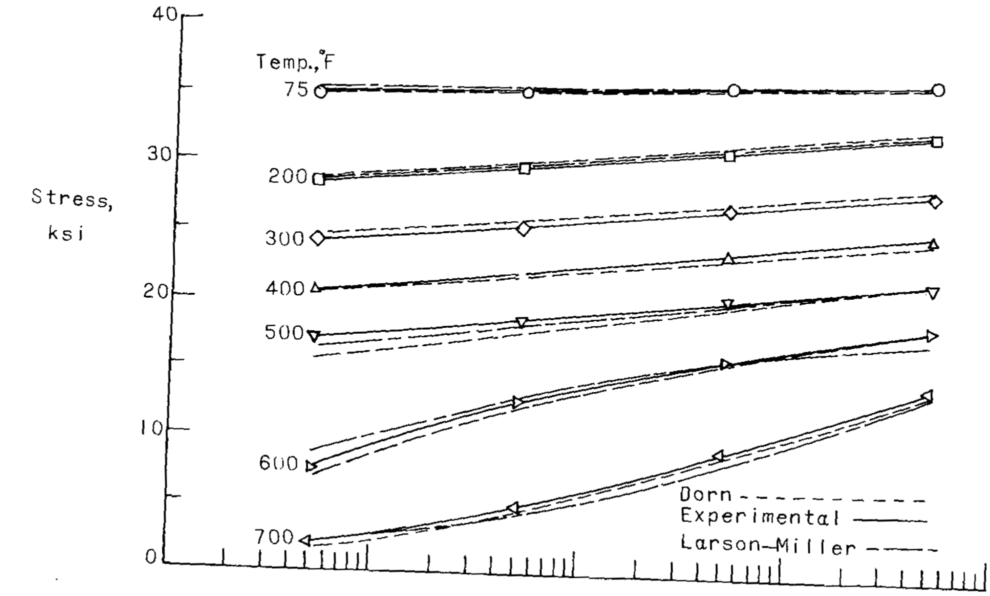


(a) Tensile strength.

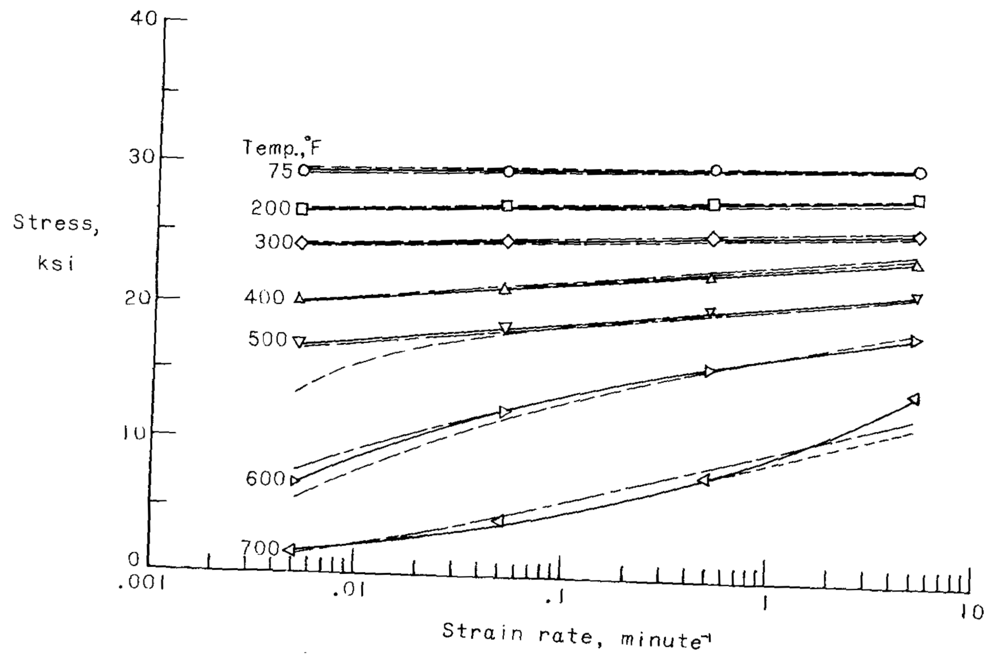


(b) Tensile yield strength.

Figure 2.- Effect of strain rate on the tensile strength and the tensile yield strength of HM21A-T8 magnesium-alloy sheet at elevated temperatures after 5 seconds' holding time at temperature.



(a) Tensile strength.



(b) Tensile yield strength.

Figure 3.- Effect of strain rate on the tensile strength and the tensile yield strength of HK31A-H24 magnesium-alloy sheet at elevated temperatures after 5 seconds' holding time at temperature.

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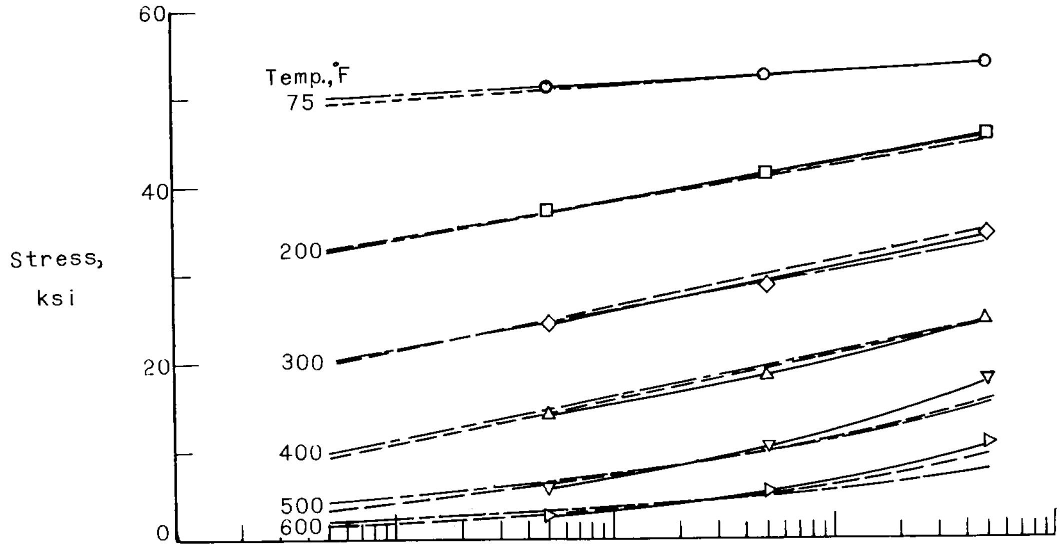
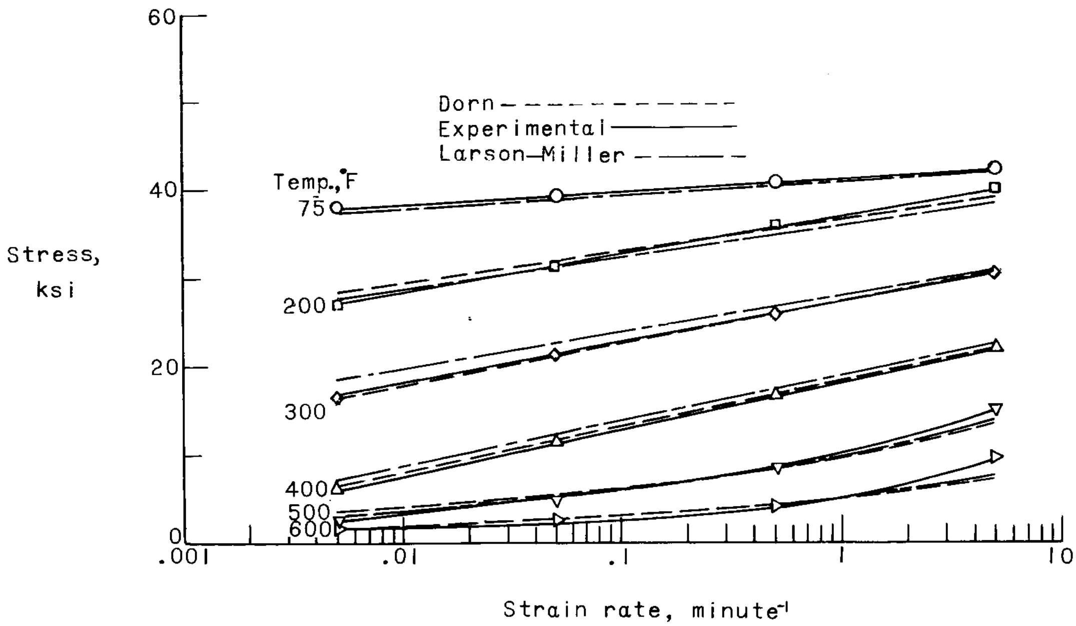
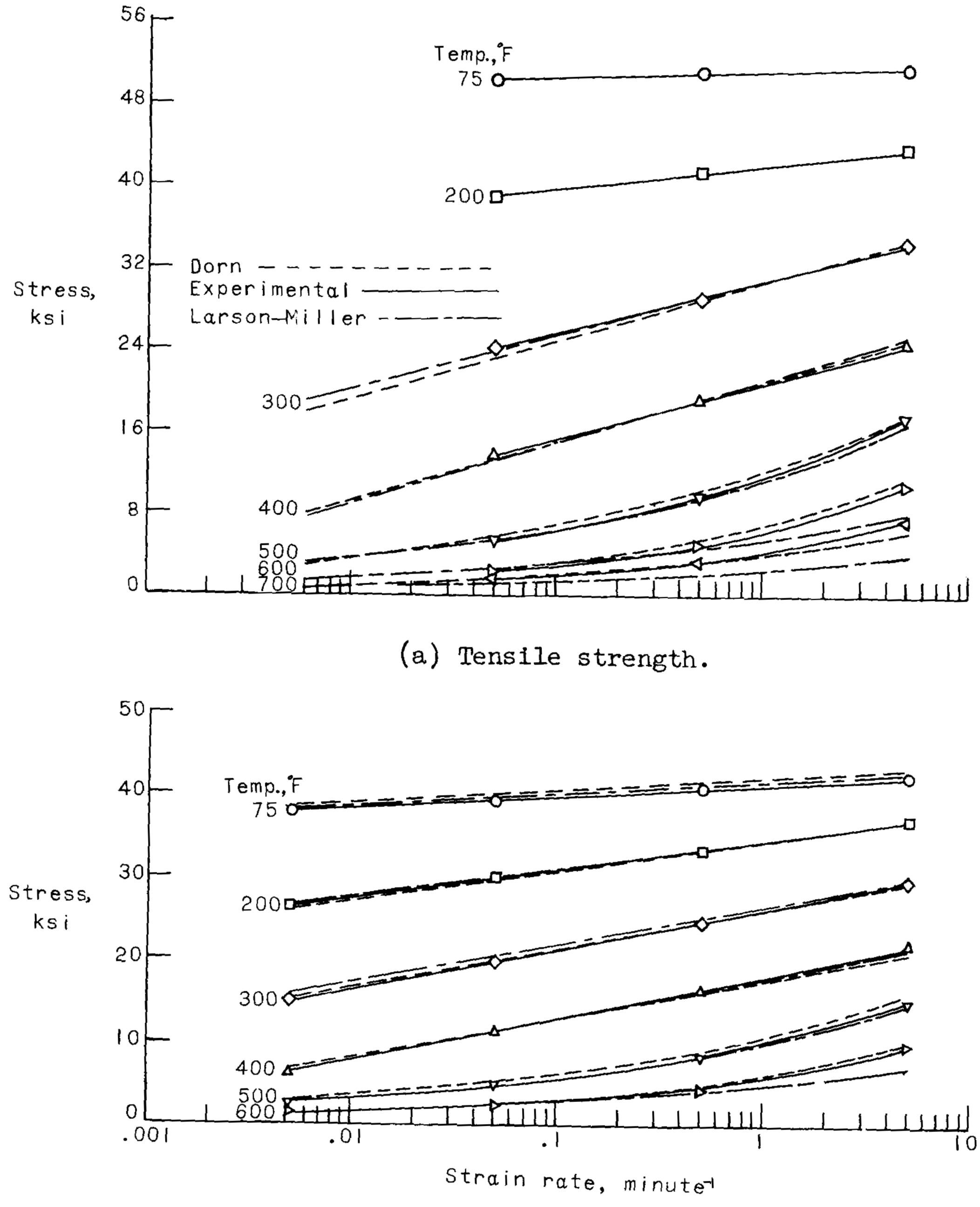


(a) Tensile strength.



(b) Tensile yield strength.

Figure 4.- Effect of strain rate on the tensile strength and the tensile yield strength of ZK60A-T5 magnesium-alloy extrusion at elevated temperatures after 5 seconds' holding time at temperature.



(a) Tensile strength.

(b) Tensile yield strength.

Figure 5.- Effect of strain rate on the tensile strength and the tensile yield strength of ZK60A-F magnesium-alloy extrusion at elevated temperatures after 5 seconds' holding time at temperature.

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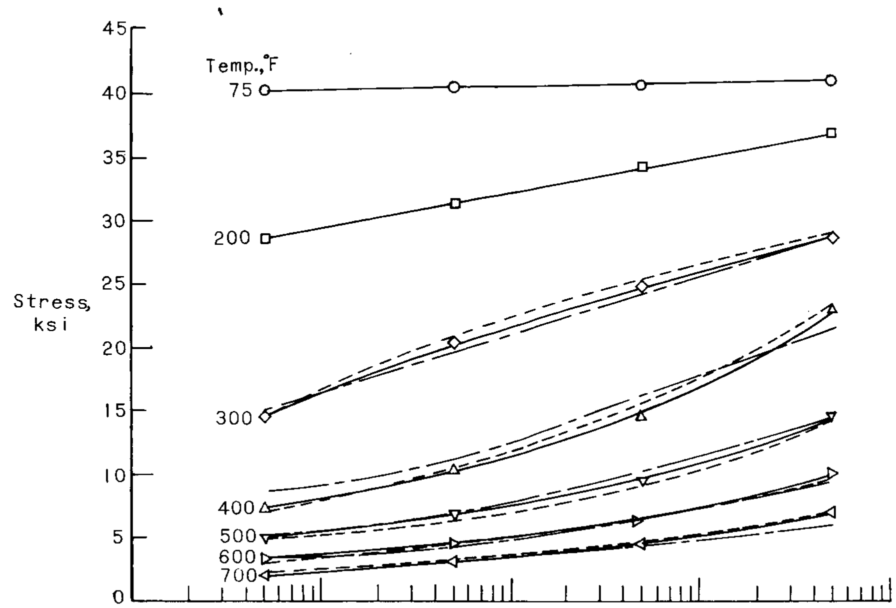
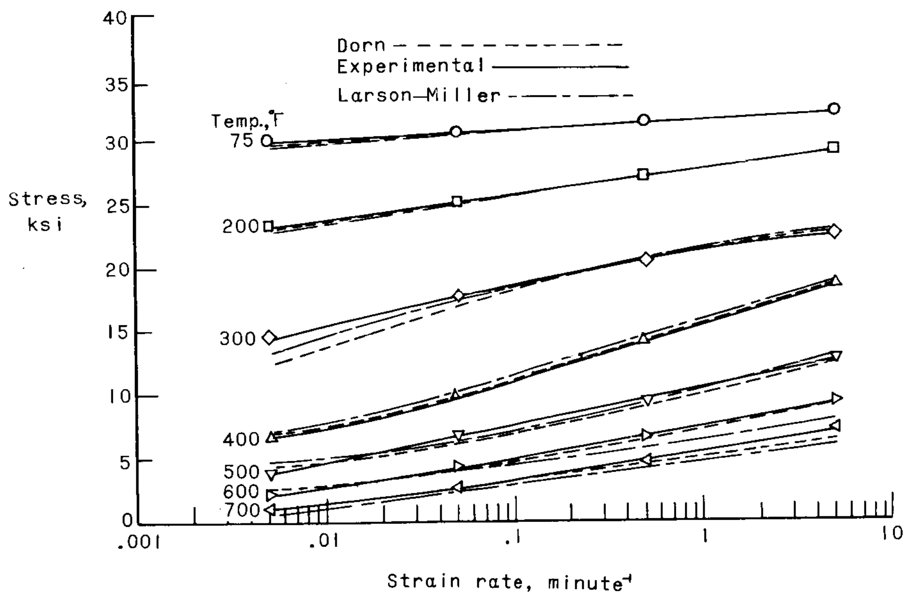


(a) Tensile strength.



(b) Tensile yield strength.

Figure 6.- Effect of strain rate on the tensile strength and the tensile yield strength of AZ31B-H24 magnesium-alloy sheet at elevated temperature after 5 seconds' holding time at temperature.

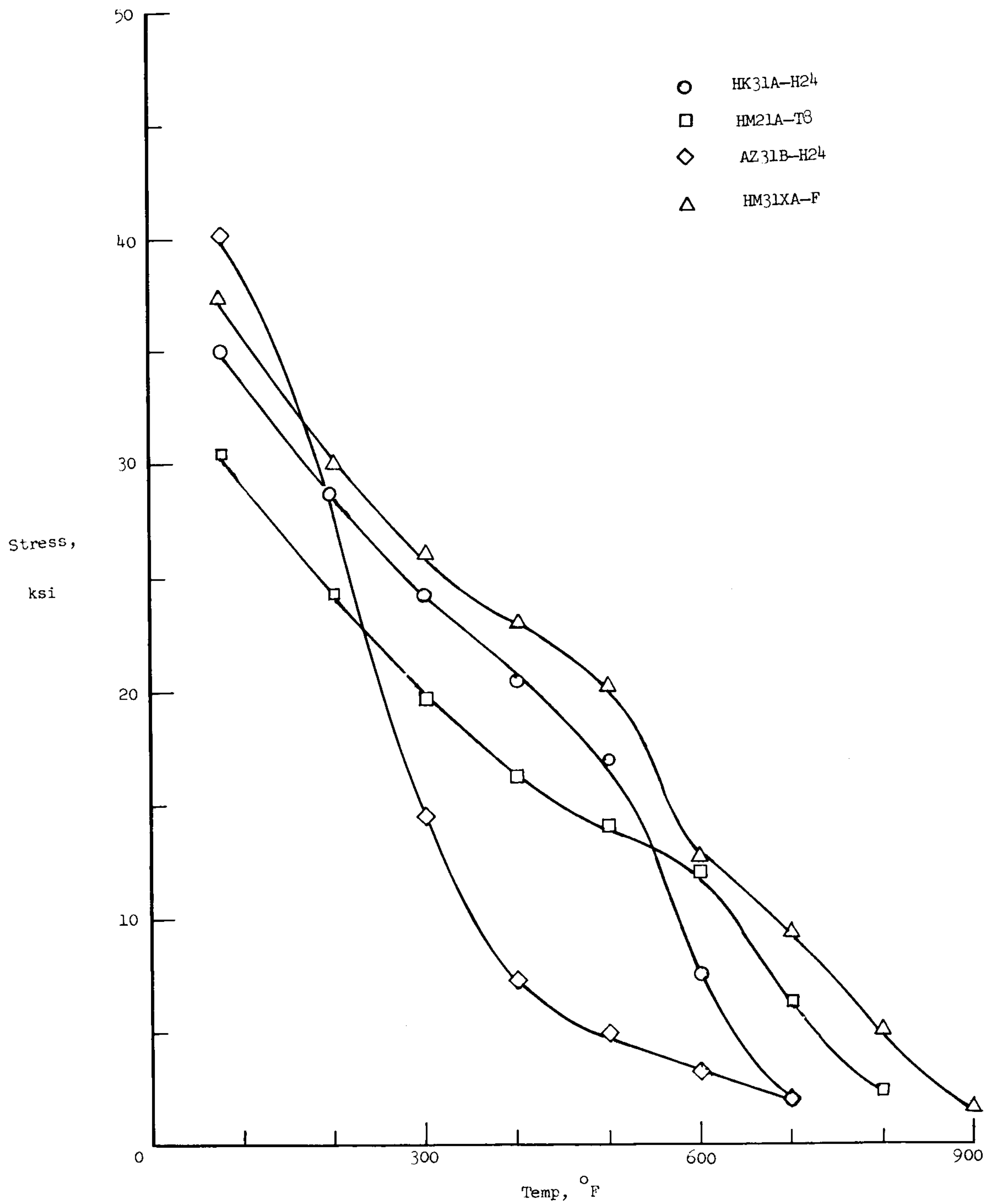


Figure 7.- Effects of temperature on the tensile strength of four magnesium alloys at a strain rate of 0.005 minute^{-1} after 5 seconds' holding time at temperature.

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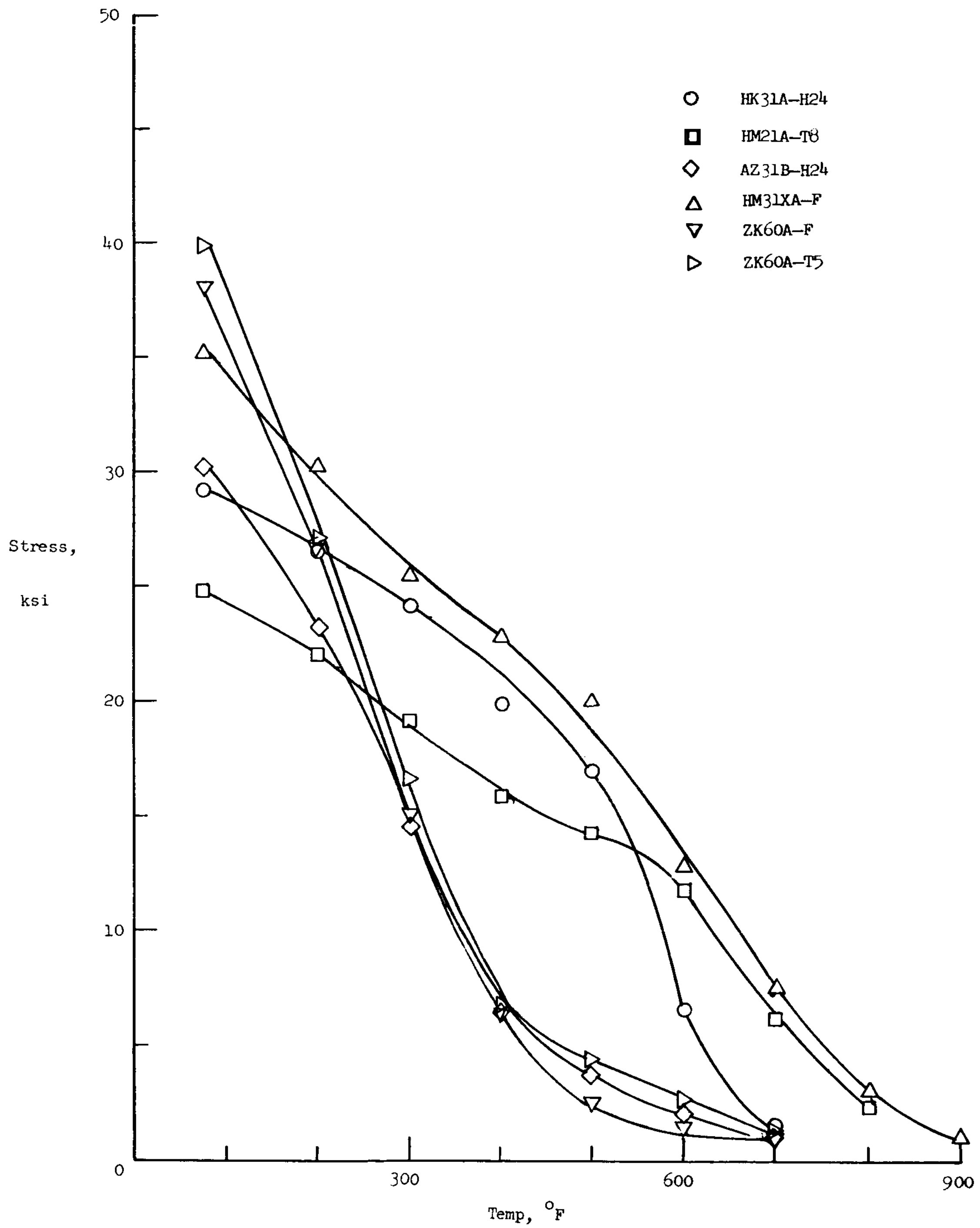


Figure 8.- Effects of temperature on the tensile yield strength of six magnesium alloys at a strain rate of 0.005 minute^{-1} after 5 seconds' holding time at temperature.

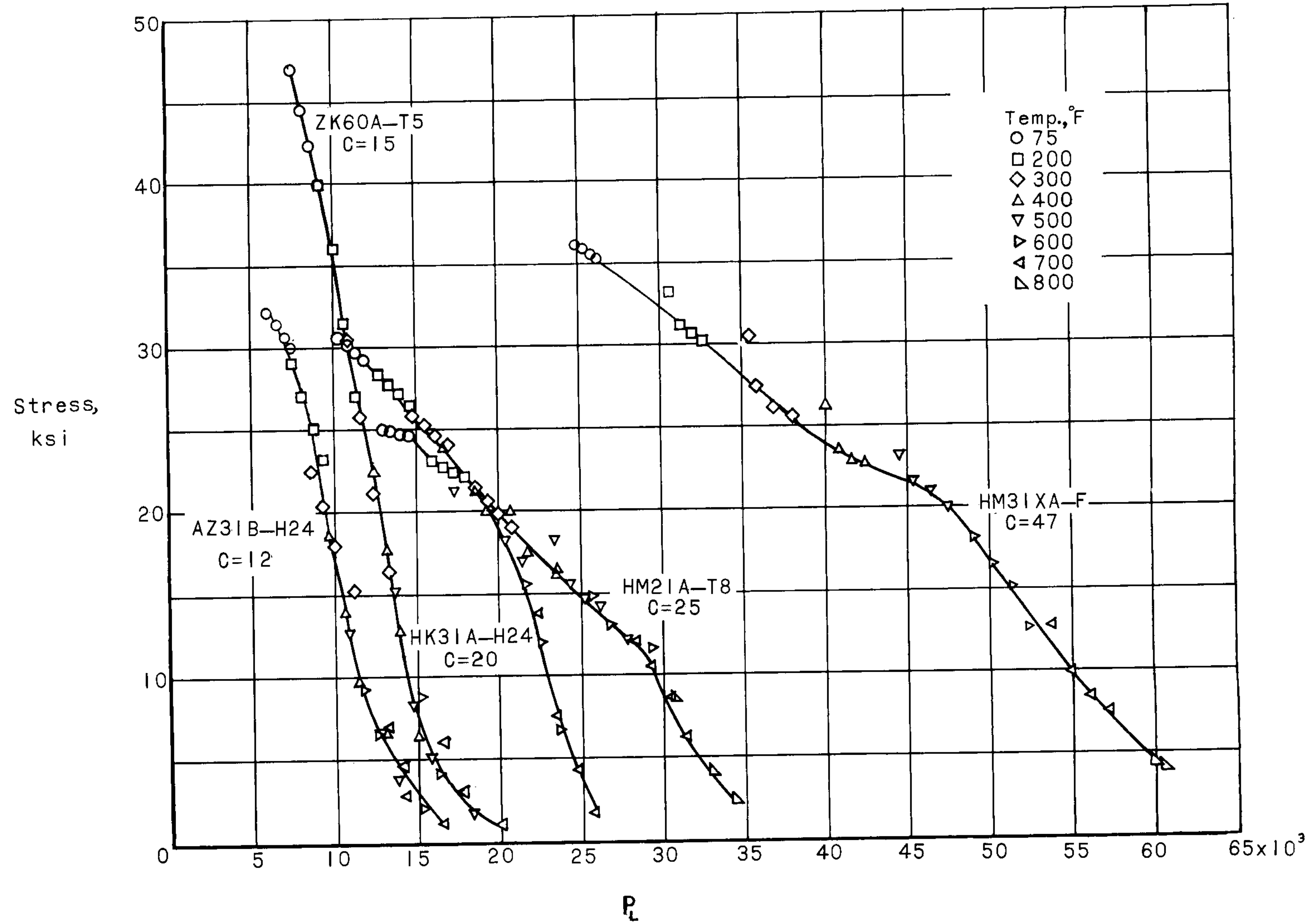


Figure 9.- Master curves for tensile yield strength of five magnesium alloys calculated by means of the Larson-Miller parameter $P_L = T(C - \log_{10} \dot{\epsilon})$.

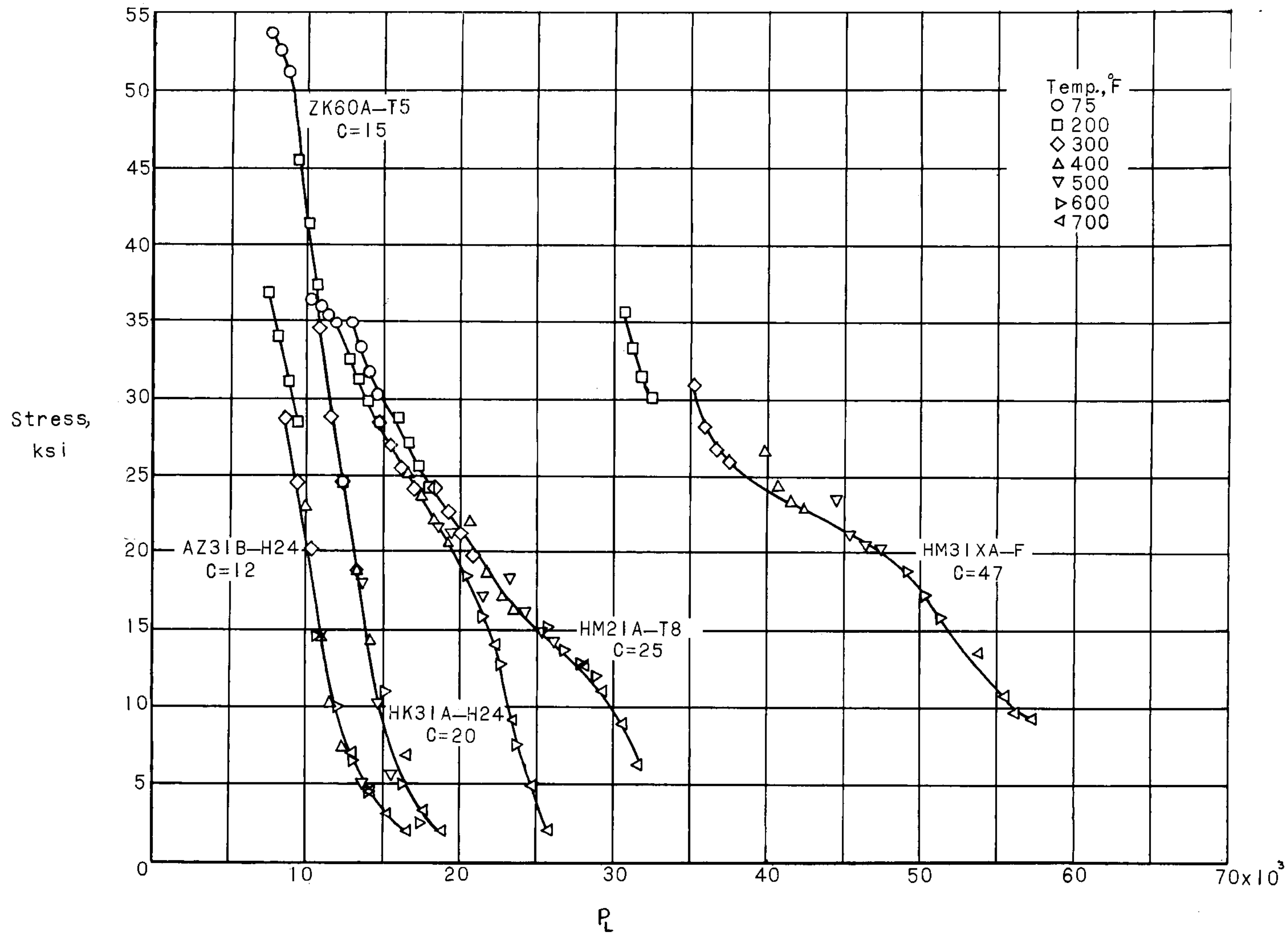
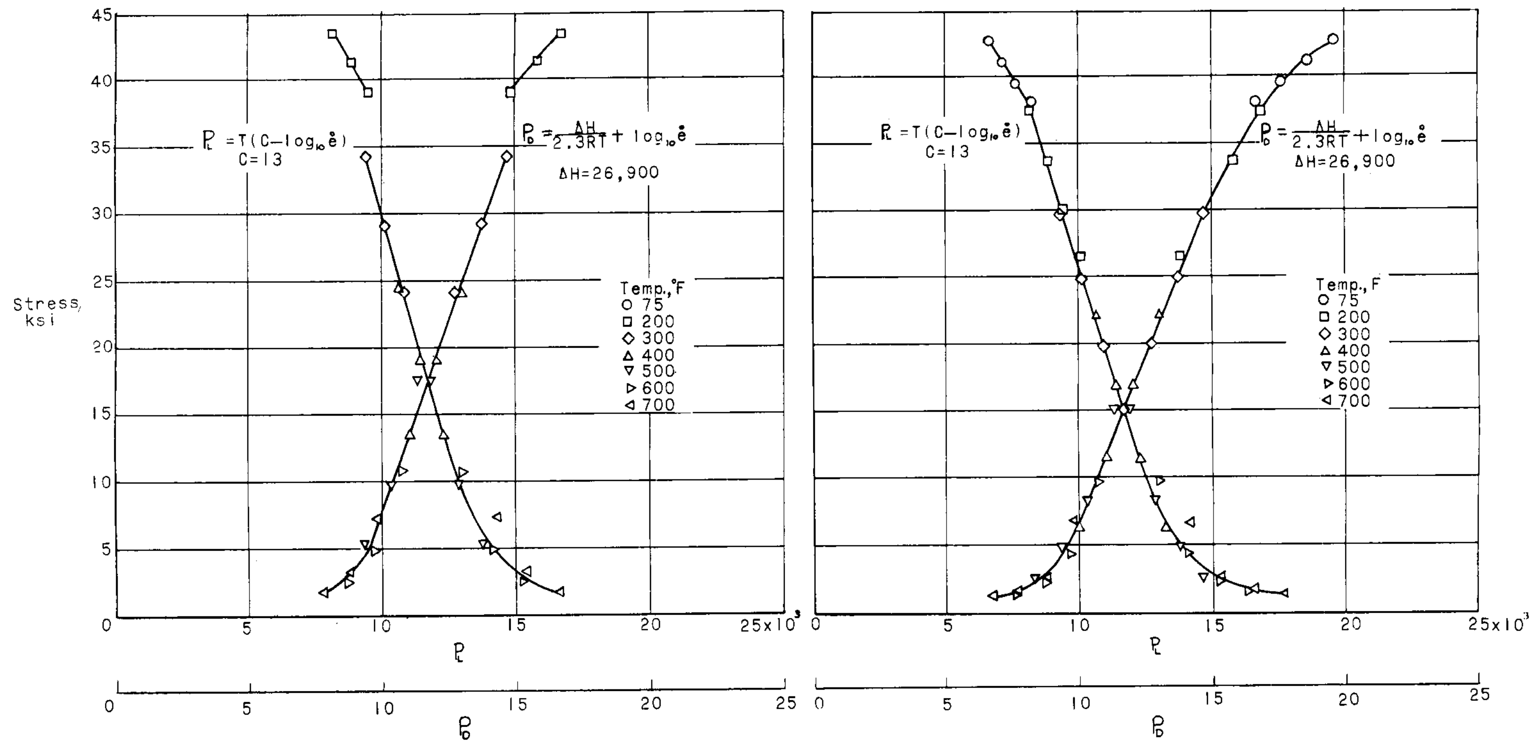


Figure 10.- Master curves for tensile strength of five magnesium alloys calculated by means of the Larson-Miller parameter $P_L = T(C - \log_{10} \dot{\epsilon})$.



(a) Tensile strength.

(b) Tensile yield strength.

Figure 11.- Master curves for tensile strength and tensile yield strength of ZK60A-F magnesium alloy calculated by means of the Larson-Miller parameter $P_L = T(C - \log_{10} \dot{\epsilon})$ and the Dorn parameter $P_D = \frac{\Delta H}{2.3RT} + \log_{10} \dot{\epsilon}$.

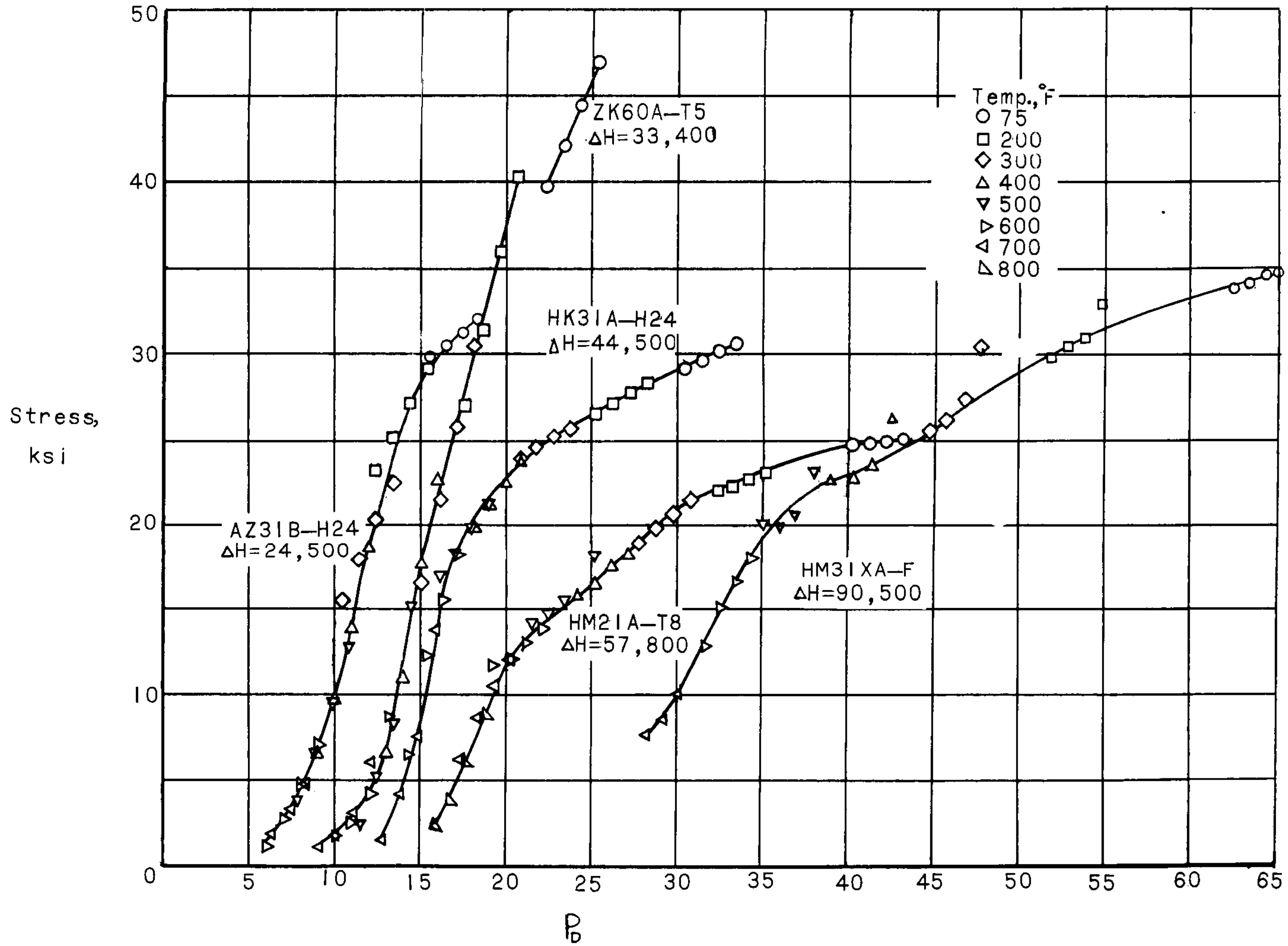


Figure 12.- Master curves for tensile yield strength of five magnesium alloys calculated by means of the Dorn parameter $P_D = \frac{\Delta H}{2.3RT} + \log_{10} \dot{\epsilon}$.

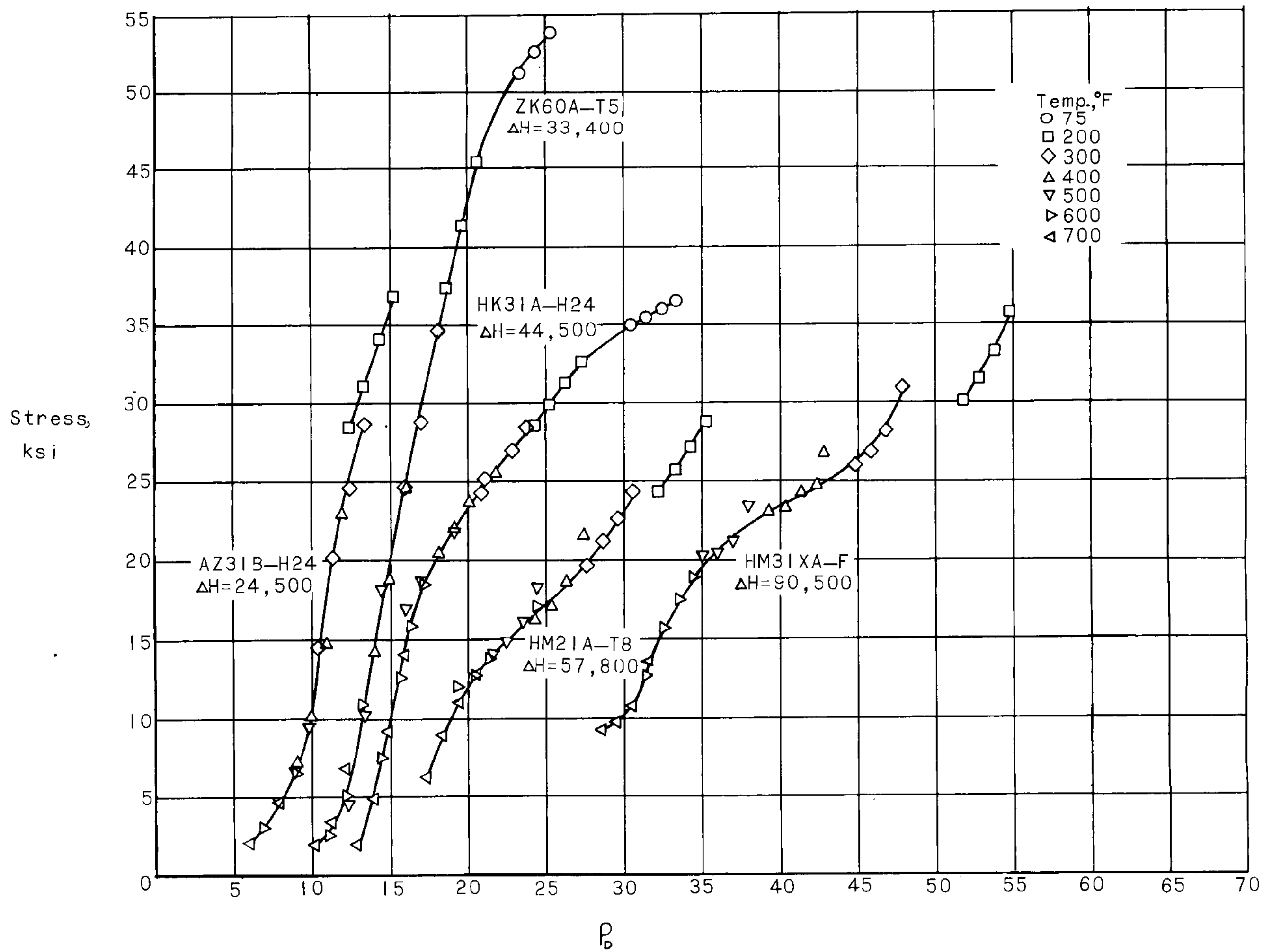


Figure 13.- Master curves for tensile strength of five magnesium alloys calculated by means of the Dorn parameter $P_D = \frac{\Delta H}{2.3RT} + \log_{10} \dot{\epsilon}$.

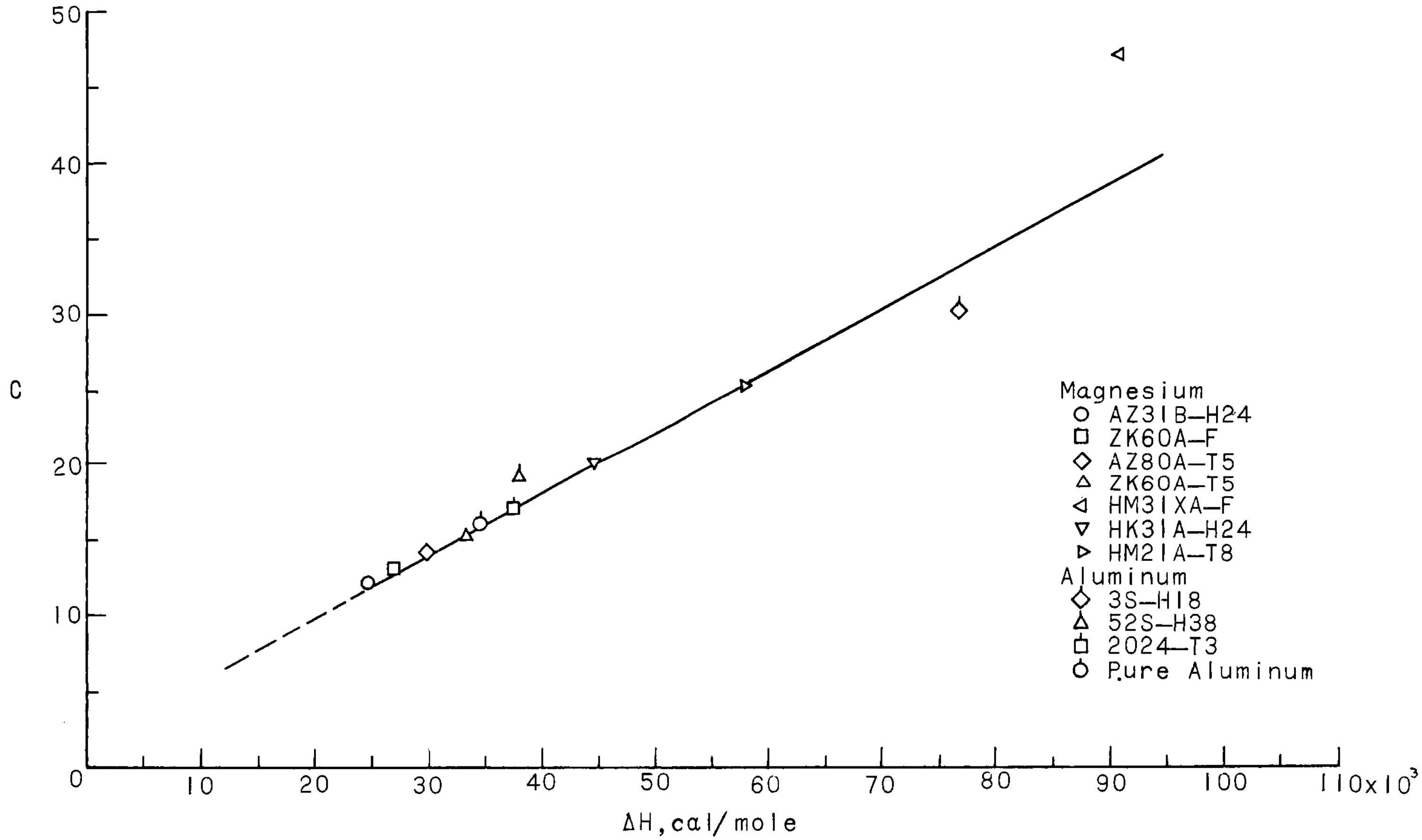


Figure 14.- A relationship between the Larson-Miller constant C and the activation energy ΔH for magnesium and aluminum alloys.

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